DOE/EPSCoR program, Building EPSCoR-State/National Laboratory Partnerships (02-04)

DOE Award Number: **DE-FG02-03ER46043**

Name of Recipient: **University of South Carolina**

Fundamental Problems of Neutron Physics at the Spallation Neutron Source at the ORNL

Principle Investigator: *Vladimir Gudkov*
Department of Physics and Astronomy
University of South Carolina, Columbia, SC 29208
Phone: (803)576-5573; Fax: (803)777-3065
E-mail: gudkov@sc.edu

Date of the Award Period: May 15, 2003-May 14, 2008
May 15, 2003-May 14, 2004 - approved budget $161,000.00
May 15, 2004-May 14, 2005 - approved budget $161,000.00
May 15, 2005-May 14, 2006 - approved budget $161,000.00
May 15, 2006-May 14, 2008 – no-cost extension

DOE laboratory collaborator: *Geoffrey L. Greene*
Cold Neutron Beam Project Leader
Physics Division
Oak Ridge National Laboratory
Bldg. 6010, Oak Ridge, TN, 37831
Phone: (865) 574-8435; Fax: (865) 576-5780
E-mail: greenegl@ornl.gov

Abstract:

We propose to provide theoretical support for the experimental program in fundamental neutron physics at the SNS. This includes the study of neutron properties, neutron beta-decay, parity violation effects and time reversal violation effects. The main purpose of the proposed research is to work on theoretical problems related to experiments which have a high priority at the SNS. Therefore, we will make a complete analysis of beta-decay process including calculations of radiative corrections and recoil corrections for angular correlations for polarized neutron decay, with an accuracy better that is supposed to be achieved in the planning experiments. Based on the results of the calculations, we will provide analysis of sensitivity of angular correlations to be able to search for the possible extensions of the Standard model. Also we will help to plan other experiments to address significant problems of modern physics and will work on their theoretical support.

Accomplishments During the Reporting Period

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) is well recognized as the most advanced neutron source in the world and foundational for many fields including fundamental neutron physics: studies of neutron properties, neutron beta-decay, parity invariance and time-reversal invariance, and nuclear astrophysics. Therefore, in order to use this facility for the purposes of fundamental physics with maximum efficiency, it is necessary to identify and develop future experimental programs that can resolve important problems of contemporary physics.

The main idea of the fundamental neutron physics experiments is as follows: instead of increasing the energy of colliding particles to probe "new physics" (the possible extensions of the Standard model), one can increase the experimental accuracy to be sensitive to small contributions from high energy region as this is critical to evaluate alternative models. However, in many cases, the advantage of high precision experiments at these energies can be diminished by possible uncertainties in the theoretical description of the process. Thus, it is extremely important to be able to describe the process with the necessary level of accuracy. In other words, it is crucial to measure parameters, which are unambiguously predicted by theory. This is why a strong collaboration between theorists and experimentalists is very important not only for the analysis of the resulting experimental data, but also for the planning of precise experiments.

The main goal of this project was to provide such theoretical support to design the most productive experimental program in fundamental neutron physics at the SNS. For example, to be able to search for the possible extensions of the Standard model in neutron decay, a complete sensitivity analysis of beta-decay process must be done based on calculations of all radiative and recoil corrections, with an accuracy better that is achieved in the planning experiments. This and other theoretical investigations can help in the finding of the best strategy for the neutron fundamental research on the SNS at the ORNL. The numerical simulations based on these theoretical results should be used to optimize the proposed experiments in fundamental neutron physics.

The initial efforts of the proposal were focused on most urgent problems related to the Fundamental Neutron Physics (FNP) project at the Spallation Neutron Source at the Oak Ridge National Laboratory. At that time, one of the highest priority experiments to be done at the FNP beam line was the "Precise Measurement of Neutron Decay Parameters." This experiment should be able to clarify the long standing unitarity problem, obtaining the CKM matrix element V_{ud} in nuclear model independent way, and to search for new physics beyond Standard Model. To be able to extract accurate information with maximal efficiency from the experimental data, the detailed theoretical analysis of all radiative and recoil corrections to the measurable parameters should be done with a better accuracy than the expected experimental accuracy.

Based on the analysis of existing calculations of radiative and recoil corrections for neutron beta decay, it was shown [1] by the PI that strong model dependent parts of the radiative corrections cannot be extracted from any set of neutron decay measurements with the currently available experimental accuracy. Therefore, alternative theoretical approaches and/or other classes of experiments should be considered in order to improve the readability of the future precise neuron decay experiments. Then, after the analysis of existing theoretical approaches for calculations of radiative and recoil corrections for neutron decay parameters, the PI suggested a new approach: comprehensive systematic calculation of radiative and recoil corrections for a complete set of angular distribution parameters of neutron beta-decay using one framework -- the effective field theory (EFT). To speed up the calculations in the EFT, the PI has involved in this research experts in the EFT and in weak interactions from US, Canada, and Japan. The accomplishment of this international collaboration of theorists is the calculation of neutron decay process in the first order of EFT [2]. Based on these calculations and on further additional analysis, we are able to answer the questions stated in the proposal, such as:

- How different are radiative corrections for the angular coefficients in the point-like nucleon approximation (ignoring strong interaction contributions)?
- What are energy dependencies on the corrections that involve strong interaction contributions?
- How do estimations of the strong interaction contributions of radiative corrections of Gamow-Teller part of the β-decay change the above results?

It should be noted that these newly obtained theoretical results also help the PI to contribute to the experimental collaboration by developing/improving simulation software based on the GEANT4 framework.

The performed calculations of neutron beta-decay parameters resulted in the exact and complete description of the process in the Standard Model with only one free low energy constant (LEC), which provides a complete description of angular correlations in the Standard Model with an accuracy of about 10^{-5} (provided that the LEC is obtained from a complementary experiment). This provides the basis for theoretical analysis of high precision experimental results and for design of new experiments. Unfortunately, we could not find a good way to obtain the required one LEC from experiments. In the case of neutron β-decay, one of the complementary processes could be a neutrino-deuteron reaction, which is rather difficult to measure with the required accuracy. To understand the feasibility of obtaining the LEC from this process, as a first step to this approach, the detailed review of existing methods of calculations of neutrino-deuteron reactions in tree approximation has been done [3].

It should be mentioned that the obtained description of the neutron decay process includes all known radiative and recoil corrections. (At this stage, we ignored contributions from electron and proton polarizations.) Therefore, we have managed to describe angular correlations in neutron decay in the Standard model with accuracy better than expected in the experiments on the SNS. This provides a "background" from which one can search for manifestation of new physics [4] since any experimental deviation from this theoretical prediction cannot be explained in the Standard model.

Using these results, we have developed a method for general analysis of the sensitivity of neutron beta-decay experiments to the possible deviations from the Standard model [5].

The contributions from models beyond the Standard model are, for low energy neutron decay, parameterized in terms of vector, axial-vector, scalar, and tensor coupling constants and in terms of parameters related to specific models. For example, we have derived the exact expressions for neutron beta decay probability, which includes all possible manifestations models beyond the Standard one up to level of 10^{-5} without time-reversal violation. Based on the general expressions for manifestation of the deviation from the standard model, we analyzed the sensitivities of all neutron decay experiments which have been done up to date [5,6]. To do this we used the obtained expression for angular correlations as a reliable parameterization for all beta-decay angular correlations in terms of only one parameter. The accuracy of this description is proven to be 10^{-5} (at this level, the second order corrections became important), provided that the LEC is fixed with the required accuracy. (This LEC can be constrained/estimated [4,6].) Then we have described the process in the Standard Model framework with accuracy better than the expected experimental accuracy and, as a consequence, we were able to study various contributions of possible deviations from predictions of the Standard Model to angular correlations in neutron decay. This leads to the estimate of the sensitivity of the observable parameters in the given experimental setup for the considered contributions from new physics. This type of analysis for existing experiments has been done by PI and his collaborators with a generic description of deviations from the Standard Model in terms of low energy coupling constants. The result of the analysis shows that angular correlation coefficients have different sensitivity to different types of interactions.

Following the "list of priorities" of future experiments, we also worked on nuclear enhancement mechanisms for symmetry violation effects in nuclei and on theoretical aspects of interactions of ultra cold neutrons with mesoscopic objects.

For example, new mechanisms of enhancement of under-the-barrier [7] and over-the-barrier [8] nuclear processes have been proposed. If they will be confirmed experimentally, these mechanisms would be explored for the possibility of enhancing parity violating effects in neutron induced reactions, as well as for other applications in nuclear physics.

During the work on the project, we have observed important features of neutrons as a probe to test "exotic" very weak non-standard interactions. There are two basic properties we have explored: coherent nature of neutron interactions in interferometry and neutron diffraction [9] and the sensitivity of neutrons with extremely low energy (down to *nano-eV* scale) -- ultra-cold neutrons (UCN) to very weak interactions [10]. It was shown [9] that the existing neutron interferometry methods can be used to increase a limit on non-Newtonian gravity (e.g. a manifestation of extra-dimensional gravity) by a few orders of magnitude. For the case of UCNs, the sensitivity of the system to a perturbation (small interactions) can roughly be estimated [10] as the ratio of the energy of perturbation and the characteristic energy of the system. From this point of view, low energy neutrons and, especially, UCNs are a very unique tool to search for new physics. Since these low energy neutrons can interact with nuclei coherently, accumulating small signals at each interaction, the expected enhancement of "exotic" very weak interactions could be many orders of magnitude. Recent exploration of this idea by the PI gives promising results and shows that neutrons can essentially improve bounds on non-Newtonian gravitational interactions (for example, on extra-dimensional gravity).

For the future measurement of neutron lifetime and neutron electric dipole moment, it is very important to have a thorough understanding of interactions of UCNs with nano-size objects. As a first step in understanding these interactions, we considered interactions of UCNs with nano-size bubbles in liquid helium [11], where analytical results can be obtained. We have calculated elastic and inelastic scattering of ultra cold neutrons on bubbles the size of nanometers. It was shown that neutron-bubble cross section is large and is sensitive to different vibration modes of bubbles. Besides the pure theoretical understanding of neutron interactions with large objects, the considered processes could be also used for the study of dynamics of nano-size bubbles in helium and for developing new methods for ultra cold neutron production [11].

The results of the research have been presented at seminars/colloquiums at the:

- TUNL, Duke University, January, 2004;
- Institute Laue-Langevin, Grenoble, France, June 2004;
- Istituto Nazionale di Fisica Nucleare, Padova, Italy, June 2004;
- North Carolina State University, April 2005
- Melbourne University, Melbourne, August 2005;
- National Institute of Standards and Technology, Gaithersburg, MD, May 2007;
- University of South Carolina, August 2007;
- University of Tennessee, February 2008;

and at the following conferences/workshops:

- International Conference IPN2003 in Japan, November 2003;
- International Conference on “Precision Measurements with Slow Neutrons” NIST, Gaithersburg, MD, April 2004;
- “From Zero to Z0: A Workshop on Precision Electroweak Physics” Fermilab, May 2004;
- “Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, and Related Topics” Dubna, Russia, May 2004;
- American Conference on Neutron Scattering, College Park, Maryland, June 2004.
- EPSCoR Conference, Argon National Laboratory, June 2004;
- Spring 2005 APS meeting, Tampa, FL, April 2005;
- Joint APS and PSJ meeting, , Kapalua, HI, September 2005;
- International Workshop on Fundamental Symmetries: from nuclei and neutrinos to the Universe ECT* Trento, Italy, June 2007;
- International Nuclear Physics Conference, INPC2007, Tokyo, Japan, June 2007;
- Renewable Energies for a Global Economy Workshop, Golden, CO, July 2007;
- International Conference on Fission and Properties of Neutron-Rich Nuclei, Sanibel Island, FL, November 2007;
- The 4th International Workshop on Nuclear and Particle Physics at J-PARC (NP08), Japan, March 2008;

- International workshop on particle physics with slow neutrons, Grenoble, France, May 2008.

In the process of the research, we came to the conclusion that it would be very important to use the expertise of the world wide community to identify important issues in nuclear physics, particle physics, astrophysics, and cosmology, which can be studied at the Fundamental Neutron Physics project at the SNS. To realize this idea, the PI organized the international workshop "Theoretical Problems in Fundamental Neutron Physics" (http://www.physics.sc.edu/TPFNP/) with the support from the Oak Ridge National Laboratory, Oak Ridge Associated Universities, Joint Institute for Neutron Science, University of South Carolina, and Sub-Z0 Working Group. The Workshop was focused on three major areas where new experimental results are anticipated: (1) The semi-leptonic weak interaction and neutron beta decay; (2) The Hadronic weak interactions and Nucleon-Nucleon interactions; (3) CP & T violation and the neutron electric dipole moment. The Workshop was held on October 14-15 on the university campus. Prominent scientists from Canada, France, Germany, Russia, UK, and USA gave lectures and exchanged research ideas at the Workshop, which was also attended by young researchers and graduate students. The total number of participants exceeded 80, and they represented almost all leading research centers in the world that are active in the field of fundamental neutron physics.

During the work on this project, the collaboration between the University of South Carolina and the Oak Ridge National Laboratory was established. As a result of this research, the University of South Carolina became a member of a number of experimental collaborations in the fundamental neutron physics program at the Spallation Neutron Source at the Oak Ridge National Laboratory, and the PI was appointed a Distinguished Visiting Scientist at the Physics Division of the ORNL. Besides the general theoretical support for planning experiments, the PI, as a member of newly established experimental collaborations, was involved in detector simulations for "Nab" and "abBA" experiments and in the development of the future program at the FNP beam line at the SNS. This research is strongly supported by the University of South Carolina.

Current participations of the PI in national / international collaborations:

1. *Fundamental Neutron Physics at the Spallation Neutron Source (FNPSNS)*
2. *abBA collaboration at the Spallation Neutron Source (ORNL).*
3. *Nab collaboration at the Spallation Neutron Source (ORNL).*
4. *PANDA collaboration at the Spallation Neutron Source (ORNL).*
5. *n^3He collaboration at the Spallation Neutron Source (ORNL).*
6. *Neutrino Studies at the Spallation Neutron Source (ORNL).*

A list of papers with DOE support acknowledgement:

1. V. Gudkov, “New generation of neutron decay experiments”, J. Neutron Research 13, 39 (2005).
2. S. Ando, H. W. Fearing, V. Gudkov, K. Kubodera, F. Myhrer, S. Nakamura and T. Sato, “Neutron beta decay in effective field theory”, Phys. Lett. B 595, 250 (2004).
3. V. Gudkov and K. Kubodera, “Solar neutrinos, SNO and neutrino-deuteron reactions”, J. Phys. G: Nucl. and Part. Phys. 29, 2597 (2003).
4. V. Gudkov, K. Kubodera and F. Myhrer, “Radiative Corrections for Neutron Decay and Search for New Physics”, J. Res. Natl. Inst. Stand. Technol., 110, 315 (2005).
5. V. Gudkov, G. L. Greene and J. R. Calarco, “General classification and analysis of neutron beta-decay experiments”, Phys. Rev. C 73, 035501 (2006).
6. V. Gudkov, “Asymmetry of recoil protons in neutron beta-decay”, Phys. Rev. C **77**, 045502 (2008).
7. B. Ivlev and V. Gudkov, “New Enhanced Tunneling in Nuclear Processes”, Phys. Rev. C 69, 037602 (2004).
8. V. Gudkov, “A possible enhancement of nuclear fission in scattering with low energy charged particles”, Proc. Fission and Properties of Neutron-Rich Nuclei, in press.
9. G. L. Greene and V. Gudkov, “A Neutron Interferometric Method to Provide Improved Constraints on Non-Newtonian Gravity at the Nanometer Scale”, Phys. Rev. C 75, 015501 (2007).
10. V. Gudkov, H. M. Shimizu and G. L. Greene, “Parametric Resonance Enhancement in Neutron Interferometry and Application for the Search for Non-Newtonian Gravity”, submitted to Phys. Rev. C.
11. V. Gudkov, “Scattering of Ultra Cold Neutrons on Nano-size Bubbles”, NIM A580, 1390 (2007).

A list of people who worked on the project:

During the duration of the project, the fund was used to support the PI and three graduate students: Barbara Szczerbinska (1.5 years), Peng Liang (1.5 years) and Vladimir Montealegre (5 months).

A list of other support:

Pending support: Department of Energy, “Fundamental Neutron Physics: Theory and Analysis”, 05/16/2008 – 05/15/2011. $491,000.00

To be able to continue research theoretical aspects of fundamental neutron physics and to work on the projects of established collaborations with Oak Ridge National Laboratory and Universities, the PI has applied for new DOE grant.

Cost status:

The approved budget for the proposal includes the DOE share of $435,000.00 and the SC EPSCoR share of $48,000.00. The actual cost is equal to the approved budget.